

A new methodology for estimating forest NPP based on forest inventory data---- a case study of Chinese pine forest

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Abstract: Accurately estimating forest net primary productivity (NPP) plays an important role in study of global carbon budget. A NPP model reflecting the synthetic effects of both biotic (forest stand age, A and stem volume, V) and climatic factors (mean annual actual evapotranspiration, E) was developed for Chinese pine (*Pinus tabulaeformis*) forest by making full use of Forest Inventory Data (FID) and dynamically assessing forest productivity. The NPP of Chinese pine forest was estimated by using this model and the fourth FID (1989-1993), and the spatial pattern of NPP of Chinese pine forest was given by Geography Information System (GIS) software. The results indicated that mean NPP value of Chinese pine forest was $7.82 \text{ t m}^{-2} \text{ a}^{-1}$ and varied at the range of $3.32\text{-}11.87 \text{ t hm}^{-2} \text{ a}^{-1}$. NPP distribution of Chinese pine forests was significantly different in different regions, higher in the south and lower in the north of China. In terms of the main distribution regions of Chinese pine, the NPPs of Chinese pine forest in Shanxi and Shaanxi provinces were in middle level, with an average NPP of $7.4 \text{ t hm}^{-2} \text{ a}^{-1}$, that in the southern and the eastern parts (e.g. Shichuang, Hunan, Henan, and Liaoning provinces) was higher (over $7.7 \text{ t hm}^{-2} \text{ a}^{-1}$), and that in the northern part and western part (e.g. Neimenggu and Ningxia provinces) was lower (below $5 \text{ t hm}^{-2} \text{ a}^{-1}$). This study provides an efficient way for using FID to understand the dynamics of forest NPP and evaluate its effects on global climate change.

Keywords: Forest NPP; Forest inventory data; Chinese pine forest; Climatic and biotic NPP model; Spatial distribution pattern

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Introduction

Net primary productivity (NPP) represents the amount of carbon that is retained by plants after assimilation through photosynthesis and autotrophic respiration (Clark *et al.* 2001) and represents the net carbon input from atmosphere to terrestrial vegetation (Mellilo *et al.* 1993). It is a measure to evaluate forests' structure, function and quality. At the same time, NPP is also a basis for estimating the carbon budget of ecosystems and plays a key role in the understanding of carbon exchange between vegetation and atmosphere under both current climate condition and climate change caused by the human-induced increase in atmospheric CO₂ concentration (Woodward *et al.* 1995). Therefore, a better understanding of NPP of forests will improve the estimation of global carbon cycle and enhance the ability of forest management under changing global environment. Study of NPP is a core task of International Geosphere-Biosphere Program (IGBP) and Kyoto Protocol (IGBP 1998).

Forest ecosystems play a very important role in the global carbon cycle and in global climatic change (Waring

1998). Several categories of methods are used to estimate forest NPP, for example, field measurements, modeling, or a combination of both (Houghton *et al.* 2001). But they probably over-estimated or under-estimated forest NPP to different degrees (Schulze *et al.* 2000). One important reason comes from data sources (Scurlock *et al.* 1999). Forest Inventory Data (FID) is widely used in studying forest carbon cycle, for many countries periodically carry out forest inventory, and the data is accurate and systematic. How to make full use of those data for estimating forest carbon is paid attention by many researchers (Schimel *et al.* 2001; Brown 2002; Zhou *et al.* 2002).

Chinese pine (*Pinus tabulaeformis*) is a dominated species in coniferous forest of China. It is also a major species not only in reforestation and afforestation but also in wood product and protecting erosion (Xu 1981). Chinese pine is mainly distributed in the sensitive region to global climate change (Wang *et al.* 1995). Thus, it is very important to study NPP of Chinese pine and its responses to climate change. Studies on NPP of Chinese pine in China have been carried out for a long time (Chen *et al.* 1984; Guan 1986; Liu 1987; Xiao 1990; Zhang 1992), and allometry regression equations were often used to calculate NPP of Chinese pine. Although a lot of data of Chinese pine's NPP were collected, those NPP data were so scattered that could not well reflect the NPP level at regional scale. Ma (1988) estimated NPP of Chinese pine at regional scale based on the turnover rates of leaves, branches and roots, however, those parameters are difficult to be obtained at regional scale, and this method could not estimate the dynamics of NPP. Luo (1996) built the patterns of NPP for

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Chinese major forest types, but those patterns were not adaptive to Chinese pine yet. In summary, those NPP models could not be used to simulate Chinese pine's NPP at regional or national scale, on the other hand, those NPP models can not embody the impacts of climatic and biotic factors.

The objectives of this paper are: (1) to compare the data of Chinese pine's NPP with simulated NPP values by four climate-based models (Miami model, Thornthwaite model, Chikugo model, and synthetic model (Zhou *et al.* 1995) and select one climate-based NPP model which can be used to simulate the NPP of Chinese pine; (2) to develop a NPP model which can reflect the effect of climatic and biotic factors; (3) to calculate NPP of different provinces based on the developed NPP model and the fourth forest inventory data (Forest Ministry of China 1994). This study may provide a method to study the impact of global change on forest ecosystem and well manage forests under global change.

Materials and methods

Materials

Field measured data about Chinese pine forests

In the last decade years, many studies had been carried on the species composition and volume and NPP measurements about Chinese pine forests (Chen *et al.* 1984; Dong *et al.* 1980; Gao *et al.* 1987; Ma 1988, 1987; Luo 1996; Liu 1987; Guang 1986; Xiao 1987). Allometric functions between volume or NPP of various tissues and certain tree size indices (such as diameter at breast height and/or tree height) were used to estimate volume and NPP at stand level. Here, 129 sets of data about stand ages, volume and NPP, etc. were collected in different regions, and 42 groups data of different sampling plots were achieved (Table 1), based on the average values of those data with the same latitude, longitude and forest stand age.

The fourth forest inventory data (1989-1993) of Chinese pine forests

The data gave the information on stand age, total area and total stem volume for this forest type at provincial level in detail. The forest type was divided into five age classes: young forests, middle-aged forests, premature forests, mature forests and over-mature forests (Table 2).

Climatic data

Climatic data were the mean values from more than 900 standard weather stations from 1951-1980 (Chinese Central Meteorological Office 1984).

Methods

Climate-based NPP model of Chinese pine forests

In order to select a proper model which could be used to estimate Chinese pine's NPP from climatic factors the

NPP of Chinese pine forests were calculated using four models, including Miami model (Lieth 1977), Thornthwaite model (Lieth 1977), Chikugo model (Uchijima *et al.* 1985) and synthetic model (Zhou *et al.* 1995). Mean annual actual evapotranspiration (E) in Chikugo model and synthetic model could be calculated using the following equation (Zhou *et al.* 1995)

$$E = \frac{r \cdot Rn(r^2 + Rn^2 + r \cdot Rn)}{(r + Rn)(r^2 + Rn^2)} \quad (1)$$

where, E is in unit of mm, r is the mean annual precipitation (mm), Rn is the intercepted net radiation obtained by land surface (kcal cm^{-2} a^{-1}), which can be calculated through the following equations (Zhang *et al.* 1993).

$$B_T = 44.53 - 0.4887 L_{at} - 0.1092 L_{on} - 0.00353 A_{lt} \quad (2)$$

$$P_{ET} = 58.93 \times B_T \quad (3)$$

$$P_{ER} = P_{ET}/r \quad (4)$$

$$R_{DI} = 0.629 + 0.237 P_{ER} - 0.00313 P_{ER}^2 \quad (5)$$

$$R_n = 4.187 \times R_{DI} \times r \times L \quad (6)$$

where B_T is biotic temperature ($^{\circ}\text{C}$), L_{at} is latitude ($^{\circ}$), L_{on} is longitude ($^{\circ}$), A_{lt} is altitude (m), r is mean annual precipitation (mm), P_{ET} is potential evapotranspiration (mm), P_{ER} is potential evapotranspiration rate, R_{DI} is the radiative dryness index, L is the latent heat (2.459 KJ g^{-1}).

Compared NPP estimated by four climate-based NPP models with field measured NPP, one of climate-based NPP models would be selected.

Estimated NPP model of Chinese pine forests

Actual NPP can be simulated through a calibrated coefficient of potential NPP (Uchijima *et al.* 1988), while potential NPP is the maximum NPP in proper climatic conditions, and it is often called as mean climatic NPP. The actual NPP of forest is determined by biotic characteristics of forest type and stand climatic factors (Zhou *et al.* 1996). If biotic factors were considered as a calibrated coefficient of potential NPP, the actual NPP could be simulated through the following equation:

$$N_{PPa} = N_{PPc} \times F \quad (7)$$

where, N_{PPa} is actual NPP, N_{PPc} is climate-based NPP, F is calibrated parameter, which could be regarded as the impact of biotic factor on the climatic NPP.

NPP of a certain forest type had close relationship with forest stand age and biomass (Fang *et al.* 1996). To a certain degree, forest NPP could be reflected by biomass and stand age of forest. Moreover, biomass had close relationship with forest volume and age, so volume and stand age could be used to simulate forest NPP. On the other hand, forest volume and stand age embody forest biotic characteristics. As mentioned above, if the ratio of volume (V) to stand age (A) represented a calibrated coefficient of forest

N_{PPc} , Equation (7) could also be described as:

$$N_{PPa} = N_{PPc} \times f(V/A) \quad (8)$$

$$N_{PPa}/N_{PPc} = f(V/A) \quad (9)$$

where, V and A are forest volume ($m^3 \cdot hm^{-2}$) and forest

stand age (a), respectively.

Based on the first 21 group data in Table 1 and the selected climate-based NPP model, N_{PPc} of the 21 points could be calculated. Then the regression relationship between N_{PPa}/N_{PPc} and V/A was developed.

Table 1. Location, climatic factors, and forest inventory data of Chinese pine in the sampling plots

No.	Site	Longitude (°)	Latitude (°)	Altitude /m	Precipitation /mm	Temperature /°C	Age /a	Volume $/m^3 \cdot hm^{-2}$	NPP $/t \cdot hm^{-2} \cdot a^{-1}$
1	Xishan, Beijing	116.47	39.8	330	644	11.5	28	39.46	5.86
2	Xishan, Beijing	116.47	39.8	560	686	10	25	86.82	6.02
3	Xishan, Beijing	116.47	39.8	250	644	11.5	24	112.98	8.06
4	Fuxing, Liaoning	121.83	42.17	400	512	7.2	20	34.74	3.58
5	Jianmu, Liaoning	119.83	40.83	500	584	8.1	21	37.02	3.21
6	Husuan, Liaoning	124.1	41.9	190	666.9	6.72	36	240.12	12.49
7	Husuan, Liaoning	124.1	41.9	270	678.97	6.33	30	143.66	9.99
8	Fuxing, Liaoning	121.7	42	240	590.51	6.76	18	29.54	4.41
9	Fuxing, Liaoning	121.7	42	200	585.25	6.95	19	32.43	4.33
10	Fuxing, Liaoning	121.7	42	300	598.4	6.47	30	111.35	10.34
11	Tai'an, Shandong	117.2	36.4	920	998.31	8.07	29	131.81	10.79
12	Tai'an, Shandong	117.2	36.4	900	992.63	8.17	29	168.27	12.7
13	Tai'an, Shandong	117.2	36.4	950	1006.85	7.93	29	135.34	11.85
14	Tai'an, Shandong	117.2	36.4	550	893.09	9.85	23	62.84	5.72
15	Chengde, Hebei	117.97	41.62	950	586	4.3	27	81.35	7.93
16	Chengde, Hebei	118	41.5	760	549.61	5.15	27	79.82	6.81
17	Chengde, Hebei	118	41.5	770	550.65	5.1	26	67.84	6.11
18	Chengde, Hebei	118	41.5	810	554.78	4.91	24	48.88	4.82
19	Chengde, Hebei	118	41.5	750	548.58	5.2	27	58.93	5.12
20	Chengde, Hebei	117.15	41.73	1260	639	2.5	28	95.76	6.79
21	Chengde, Hebei	118	41.5	1030	577.54	3.85	26	59.23	6.55
22	Chengde, Hebei	118	41.5	865	560.47	4.65	28	69.54	5.86
23	Chengde, Hebei	118	41.5	1095	584.26	3.54	26	147.51	11.42
24	Chengde, Hebei	118	41.5	1135	588.4	3.35	25	107.36	8.67
25	Chengde, Hebei	118	41.5	1050	579.61	3.76	29	135.8	9.96
26	Chengde, Hebei	118	41.5	1040	578.57	3.81	29	91.84	7.48
27	Xianyang, Shanxi	108.15	34.03	1400	659	8.4	29	60.41	7.92
28	Ningshan, Shanxi	108.45	33.43	1660	1133	8	20	79.84	10.38
29	Yaoxian, Shanxi	107.3	34.5	900	574.96	12.29	25	90.61	9.39
30	Lantian, Shanxi	109	33.9	850	697.09	12.69	17	55.45	6.74
31	Lantian, Shanxi	109	33.9	900	698.75	12.44	19	66.04	8.22
32	Lantian, Shanxi	109	33.9	950	700.61	12.19	19	75.88	9.26
33	Lantian, Shanxi	109	33.9	970	701.41	12.09	20	83.96	10.39
34	Lantian, Shanxi	109	33.9	1030	704.01	11.79	19	70.94	7.12
35	Lantian, Shanxi	109	33.9	1000	702.68	11.94	22	114.55	11.66
36	Lantian, Shanxi	109	33.9	1090	706.91	11.49	25	116.8	11.56
37	Lantian, Shanxi	109	33.9	1125	708.74	11.31	25	50.83	5.66
38	Guangyuan, Shichuang	105.8	32.4	1500	960.72	11.15	36	317.92	15.91
39	Guangyuan, Shichuang	105.8	32.4	1540	961.01	10.98	36	220.11	12.17
40	Taiyue, Shanxi	112	36.7	1550	618.84	6.23	27	77.7	8.53
41	Chifeng, Neimenggu	119	42.3	700	389.41	4.38	17	69.42	5.6
42	Chifeng, Neimenggu	118.97	42.27	750	390	0.6	21	70.36	5.4

NPP distribution pattern of Chinese pine forests

Based on 30-year average climatic data (1951-1980) from more than 900 standard meteorological stations in China, average E of different provinces can be calculated by using the methods of Zhang (1993) and Zhou (1995). The minimum and maximum values of every age class are selected in the stand ages, and the NPP of every age class

was the NPP mean values of the two extremely stand ages on the basis of using climatic and biotic NPP model to calculate NPP from forest inventory. NPP of one province was the average of five stand age classes. NPP distribution pattern of Chinese pine could be built by linking GIS software.

Table 2. Volume and area of Chinese pine forests of five age classes in different provinces

Provinces	A(0-10)		B(11-30)		C(31-50)		D(51-80)		E(>81)		Total	
	Volume	Area	Volume	Area	Volume	Area	Volume	Area	Volume	Area	Volume	Area
Beijing	1405	110	4891	138	557	16	143	4	-	-	6996	268
Tianjin	47	16	396	12	-	-	-	-	-	-	445	28
Hebei	18148	1286	49757	1022	5524	65	-	-	-	-	73429	2373
Shanxi	29505	1363	94753	1756	25223	289	544	8	-	-	150025	3416
Neimenggu	3440	990	12937	259	4089	64	-	-	-	-	20466	1313
Liaoning	29714	2773	62706	1284	4203	32	-	-	-	-	96623	4089
Shandong	9401	1472	15751	608	-	-	-	-	-	-	25152	2080
Henan	7803	421	11429	193	1137	16	-	-	-	-	20369	630
Hubei	396	30	1963	105	-	-	-	-	-	-	2359	135
Shichuang	823	353	18799	354	11992	96	6628	32	14493	64	52735	899
Shaanxi	14613	1373	59392	1471	15937	192	20806	192	29923	224	140671	3452
Ganshu	5473	243	8958	106	6088	42	9033	80	6889	36	36441	487
Qinghai	335	4	2790	28	441	4	-	-	-	-	3566	36
Ningxia	-	-	2227	28	417	4	389	4	-	-	3033	36
Total	134011	10754	465103	8282	110294	1015	979821	3853	880841	2753	2570604	26645

Notes: A (0-10), B (11-30), C (31-50), D (51-80), E (>81) are the forest age classes of different age classes. A is young forests; B is middle-mature forests; C is pre-mature forests; D is mature forests, E is over-mature forests. Volume is in unit of 100 m³. Area is in unit of 100 hm².

Results

Climate-based NPP model of Chinese pine forests

The comparisons of NPP estimated by four climate-based models were given in Table 3 and Fig.1.

Table 3 showed that the four climate-based models could not simulate Chinese pine NPP very well because the simulated NPP values based on four climate-based NPP models were not correspondence with the observed data, when the correlative coefficients (R^2) between the simulated NPP and observed NPP values were lower than 0.4. Though R^2 between the observed NPP values and simulated values by Synthetic model was higher than others, parameters in Synthetic model are more than those by the other models, and which are difficult to be achieved. The simulated efficiency of Chikugo model and Thornthwaite model were similar ($R^2=0.36$), for the parameters in Chikugo model were more than those by the other model, that to say, considering the simulated efficiency and the parameters would be used in calculating NPP. Thornthwaite Memorial model was selected as the climate-based NPP model of Chinese pine.

$$N_{PPc} = 30 \times (1 - e^{-0.0009695E}) \quad (10)$$

where, N_{PPc} is the selected climate-based NPP of Chinese pine in unit of t·hm⁻²·a⁻¹.

Table 3. Comparisons between the observed NPP and simulated NPP of Chinese pine forests in China

Climate-based NPP models	Regression equations	Correlative coefficient (R^2)
Miami model	$Y = 0.27X + 0.11$	0.07
Thornthwaite Memorial model	$Y = 0.49X + 10.02$	0.36
Chikugo model	$Y = 0.65X + 9.11$	0.36
Synthetic model	$Y = 0.57X + 6.99$	0.37

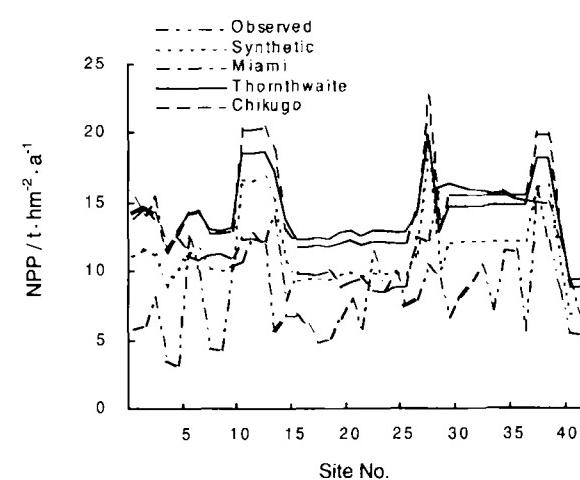


Fig. 1 Comparisons between the observed and simulated NPP values of Chinese pine forests

Fig.1 showed that the simulated NPP values of Chinese pine forests were higher than the field measured NPP, and those models could not correctly be used to simulate NPP of Chinese pine forests. One important reason was that climate-based NPP model was only considered as the influences of climatic factors and neglected the influences of biotic factors. So the simulated NPP were potential NPP.

Climatic and biotic NPP model of Chinese pine forests

Based on the first 21 groups data about Chinese pine NPP, volume, stand ages, corresponding climatic data (Table 1), and climate-based model of Chinese pine (Eq.10), the function of (N_{PPa}/N_{PPc}) and V/A could be developed through regression analysis method (Fig. 2):

$$N_{PPa}/N_{PPc} = 0.3126 \ln(V/A) + 0.1683 \quad (11)$$

where, $R^2 = 0.714$ $n = 21$.

Based on Eqs. (8), (9), (10) and (11), NPP model reflecting the synthetic effects of both biotic and climatic factors could be built:

$$N_{PPa} = \left[0.3126 \ln\left(\frac{V}{A}\right) + 0.1683 \right] \times 30 (1 - e^{-0.0009695 E}) \quad (12)$$

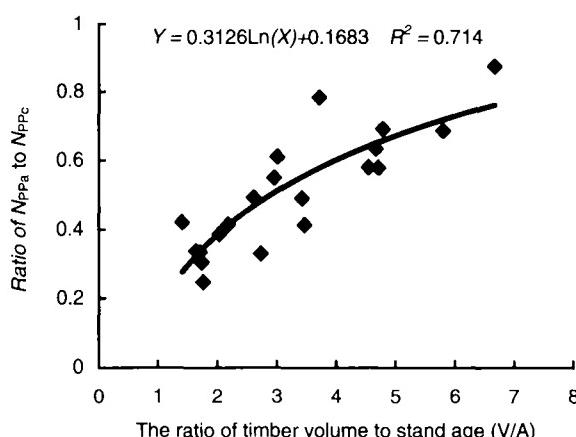


Fig. 2 Biotic function of Chinese pine forests

Model testing

The remaining 21 sets of data in Table 1 which did not take part in calculating climatic and biotic NPP model of Chinese pine were used to validate NPP model (Eq. 12). In order to obtain a more detailed assessment of the model's capability to simulate Chinese pine's NPP, two indices were used, which often were applied to evaluate agreement between model results and measured data:

(1) The mean absolute deviation D_{abs}

$$D_{abs} = \frac{1}{n} \sum_{i=1}^n |X_{mod} - X_{dat}| \quad (13)$$

where, X_{mod} and X_{dat} designate the model and measured values of the same property, and n ($i=1, 2, 3, \dots, n$) is the number of samples ($n = 21$).

The mean absolute deviation of empirical data from model is $D_{abs} = 0.59$ ($t \text{ hm}^{-2} \text{ a}^{-1}$). For the whole sampling sites, the error of the model is equal to 3.7% of the maximum NPP value of NPP_{max} ($15.91 t \text{ hm}^{-2} \text{ a}^{-1}$).

(2) The slope coefficient, b , in the formal regression equation of the field data on the corresponding model values:

$$X_{dat} = a + bX_{mod} \quad (14)$$

where, X_{dat} and X_{mod} are the measured and the simulated values, respectively; a and b are constants.

Under the assumption of full model adequacy the intercept $a=0$ and the slope $b=1$. Therefore, the test criteria will be made relative to the closeness of b to 1. After calculating, the regression line is:

$$X_{dat} = 1.4558 + 0.8933X_{mod} \quad (15)$$

where, $R^2 = 0.8026$, $n = 21$; R is correlative coefficient, n is sampling number. The regression passed through the testing of $\alpha = 0.01$, slope of X_{dat} versus X_{mod} ($b = 0.8933$) is close to 1.

The two indices showed that the climatic and biotic NPP model (Eq.12) could be used to evaluate actual NPP of Chinese pine forest. Since the first index (D_{abs}) is biased for point-to-point comparison, and the second index (slope b) is characterizing the general pattern of points on the (X_{mod}, X_{dat}) plane, combined use of both indices will help to assess the agreement between model and data more comprehensively.

NPP spatial pattern of Chinese pine forest

The spatial pattern of NPP of Chinese pine forest was shown in Fig.3. The NPP of Chinese pine forest showed strong regional variations in China, ranged from $3.32 t \text{ hm}^{-2} \text{ a}^{-1}$ to $11.87 t \text{ hm}^{-2} \text{ a}^{-1}$, with a mean value of $7.82 t \text{ hm}^{-2} \text{ a}^{-1}$. Regions with higher NPP were found in the southern and western parts of China, where NPP values are higher than $7.7 t \text{ hm}^{-2} \text{ a}^{-1}$ (Shichuang, Hubei, Henan, Liaoning provinces). Lower values of NPP were found in the northern and eastern parts, which were lower than $5.5 t \text{ hm}^{-2} \text{ a}^{-1}$. NPP in the main distribution regions of Chinese pine forests (Shanxi and Shaanxi provinces) and ranged from 5.5 to $7.7 t \text{ hm}^{-2} \text{ a}^{-1}$. The important reasons of that spatial pattern were that Chinese pine was an important planted forest species (Xu 1993), and the south of the main distributed regions had mainly young or middle-age forests. On the other hand, forests need suitable environmental conditions, while the north of China (Neimenggu and Ningxia) was the arid or semi-arid regions, where NPP of Chinese pine forest was lower than that in the south. The

results confirmed the conclusion of Ma's (1989).

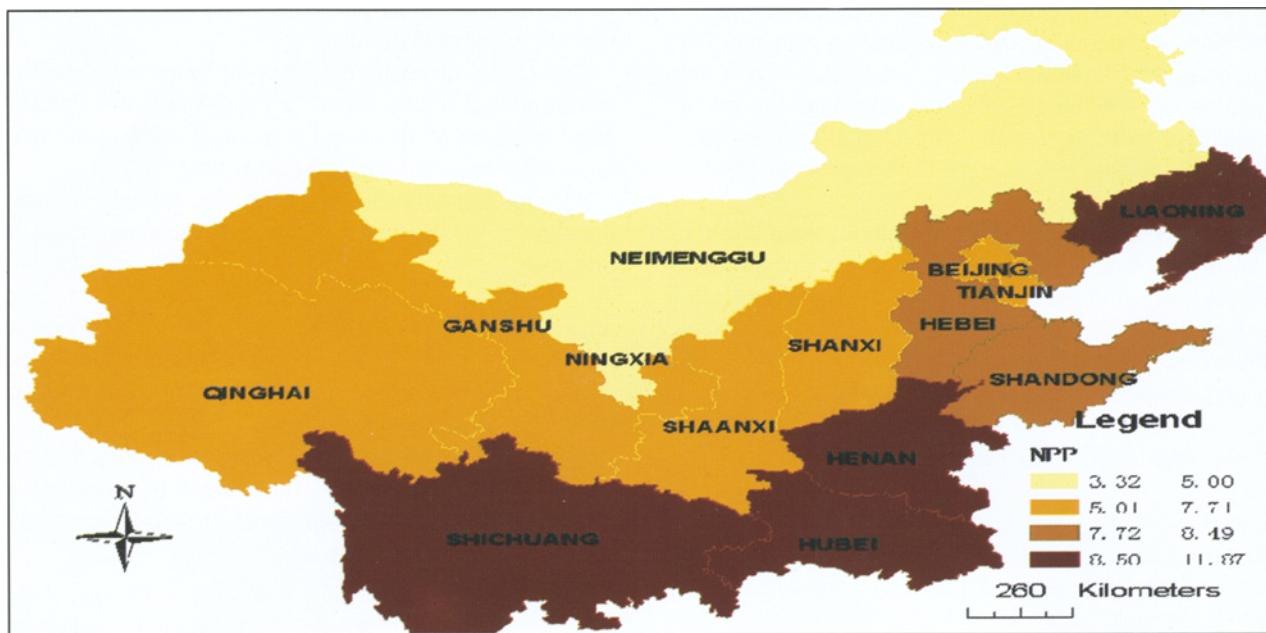


Fig. 3 NPP distribution pattern of Chinese pine forests in different provinces of China (unit: $t \cdot hm^{-2} \cdot a^{-1}$)

Discussion

NPP model

Two basic approaches have been used to model the terrestrial NPP: regression and process-based models (McGuire *et al.* 1993). Regression models demand fewer ecosystem-specific parameters than process-based models do, and they can still be useful tools for studying on the terrestrial ecosystem carbon circle (Peng *et al.* 1997). The regression-based NPP model which was built in this study has the following values: (1) The NPP model includes the synthetic abiotic and biotic impacts on forest NPP. On the other hand, the model can be used to evaluate NPP of a certain forest types at a regional scale, which overcomes the disadvantages of those climate-based NPP models (e.g. Miami model, Thornthwaite Memorial model, etc.). Those climate-based models estimate the potential NPP of a whole ecosystem at a large scale and can not evaluate NPP of a certain forest type. They also can not reflect the dynamic change of NPP (Zhao *et al.* 1998; Running *et al.* 1991). (2) Climatic and biotic NPP model may provide a good way to make full use of FID. Forest inventory data have been conducted periodically in many countries, especially in high latitude countries. China has been carried out forest inventory (generally five-year cycles) for more than 30 years by using the methods of ground surveys and remote sensing. Those data are very systematic and continuing. Many studies about forest carbon cycle have been done based on those data (Turner *et al.* 1995; Brown *et al.* 1999; Schroeder *et al.* 1997; Murillo 1997; Fang *et al.* 2001;

Goodale *et al.* 2002). However, how to use them for estimating Chinese forest NPP is paid less attention in China. NPP model developed in this study may be a good case. (3) The model includes the influence of the climatic factors to forest NPP, so the changes of Chinese forest NPP under climate changes could be predicated, which may be useful in studying the responses of forest NPP to climate changes.

Comparison of the simulated NPP of Chinese pine with that of other studies

NPP of Chinese pine is not distributed evenly across regions. The current spatial pattern is the combined result of environment factors and human activities. Because of China's forest policy, China has become one of the largest planted forest countries in the world, (Zhang *et al.* 2000). A large-scale increase of plantation-style forests in non-forested areas increased the total forest coverage in China from 5.2% in 1950 to 13.9% in 1995 (Liu 1996). Chinese pine forest as an important plantation forests plays a key role. The NPP spatial pattern is similar with the result of Ma's (1989) and Wang's study (1995).

However, the simulated mean NPP values are lower than the observed values. The major reason comes from the data that we used in this study (eg. FID). Although FID have many advantages in estimating forest carbon (Grame *et al.* 2001), FID only comprise the data of those trees with the diameter over 10 cm or 4 cm (Fang *et al.* 1998; Brown *et al.* 1999). Furthermore, the data do not include the data on herb, litter, and stand dead woods, etc. (Luo *et al.* 1999). Based on Duvigneaud (1987), the proportion of litter bio-

mass to total biomass in major biomes of the world is 2%-7% for forest, 10%-20% for tundra, 42%-55% for grasslands, and 28%-38% for deserts. Generally speaking, 25% aboveground NPP is the root NPP (Whittaker *et al.* 1975). Otherwise, there are some uncertainties in estimating NPP of Chinese pine. Many observed data come from pre-mature forests; using those data to built regression equation has limitation, which needs improved method to resolve the problem.

Future direction

As mentioned above, there have been many uncertainties in estimating forest carbon. These uncertainties can be reduced to acceptable levels with the application of appropriate inventory techniques. Recently, a report from the Global Terrestrial Observation System (GTOS) and Terrestrial Carbon Observation (TCO) Synthesis Workshop suggested two-pronged approaches: (1) developing methods for using the existing forest data and inventories to improve estimates of carbon fluxes; (2) increasing access to quality forest biomass data. Uncertainty at regional and global scales could be reduced by improving spatially extensive observations that are temporally repeatable inventories (Schimel *et al.* 2001).

Remote sensing offers a consistent and readily updated source of information for the quantification monitoring and verification of aboveground carbon sinks from regional to global scales (Curran *et al.* 1994), so remote sensing data may provide a useful means for measuring carbon stocks in forests (Jiang *et al.* 1999). A promising advance in remote measurements, e.g. scanning lidar (a pulsed laser), new type of sensor that explicitly measures canopy height, the VCL mission (the Vegetation Canopy Lidar Mission—VCL), improve the ability to successfully measure forests carbon (Means *et al.* 1999; Lefsky *et al.* 1999).

Remote sensing applications, coupled with the development of spot data-based and ecological process-based models and spatial analysis by GIS software, will improve the ability of estimating forest vegetation carbon.

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